APPENDIX D:
MAPPING CHLOROPHYLL DISTRIBUTION OVER LAKES OF NORTHWEST MONTANA

Mapping chlorophyll distribution over lakes of northwest Montana

10/01

Satellite Data

The distribution of the chlorophyll was estimated and mapped over lakes of northwest Montana, specifically around the flathead lake region using Landsat/Thematic Mapper. Landsat TM (Thematic Mapper) and ETM+(Enhanced Thematic Mapper Plus) have been widely used for monitoring of inland water quality parameters both because of the sufficient spatial resolution and because of the suitable spectral range of data acquisition. For this analysis we acquired 5 satellite images during the months of July/August from 1984 through 1999. The scenes for the years 1984, 1986, 1991 and 1996 are from the TM sensor onboard the Landsat 5 satellite, while the image for year 1999 is from the ETM+ onboard the Landsat 7 satellite.

Atmospheric corrections:

Atmospheric conditions play a key role in determining the amount of reflected radiation reaching the satellite sensors. In order to estimate lake quality parameters such as chlorophyll, one must remove the atmospheric contribution before converting the reflectances to measures of lake quality. The atmosphere affects the radiance leaving the water bodies through scattering caused by molecules and aerosols. In general, the water-leaving radiance detected by the sensor is very low with respect to the contribution of the atmosphere. There are numerous atmospheric models for accounting for the atmospheric contribution. To atmospherically correct the images used in our analysis, we used the atmospheric correction provided for TM data calibration with the image processing software ENVI 3.2. The ETM+ scene for 1999 was corrected independently by applying the correction suggested by the Landsat-7 Science Data User's Handbook.

Estimation of chlorophyll distribution from water reflectance

The estimation of the chlorophyll concentration makes use of the spectral properties of the water bodies within the optical and near infrared portion of the electromagnetic spectrum. Bands 1 to 4 (from 450 nm to 900 nm) are in the spectral range where light penetrates the water to a sufficient depth to extract information about the water quality. The presence of chlorophyll *a* and aquatic humus determines attenuation in the reflectance in band 1 (blue) and 3 (red), and an increase in reflectance in band 2 (green). The attenuation of reflectance in band 3 is lower than in band 1 due to the counteracting backscattering of suspended sediments. To develop an algorithm for chlorophyll estimation using TM data, the effect of the total suspended sediment on reflectance should therefore be taken into consideration. By subtracting band 3 from the reflectance in band 1, a correction for the additional radiance caused by scattering of non-organic sediment is introduced. For our analysis we adopted a model suggested by Brivio et al (2001), where the atmospherically corrected reflectances in band 1 and 3 are normalized by the reflectance in band2:

$$chl = 0.098 \bullet \frac{band1 - band3}{band2} \quad \mathbf{(1)}$$

This model was applied to all the 5 Landsat scenes to estimate the spatial distribution of chlorophyll in the Flathead Lake.

Registration and land masking

In order to facilitate the comparison of the chlorophyll distribution in the Flathead and Swan lakes, the 5 Landsat scenes were co-registered to the UTM projection, zone 11, datum Clarke 1866. A mask to isolate the water bodies was obtained through an unsupervised classification of band 4 (near-infrared). In the near infrared the absorption by the water is very high in contrast to the surrounding land areas. This characteristic makes the creation of a mask to isolate the water bodies relatively easy task. In the image of July 20 1991 some clouds where present in the western part of the scene during its acquisition. Since clouds also absorb in the near-infrared, they where included into the mask.

Results and Discussion

Figure 1 presents the distribution of the chlorophyll concentration in μg/l predicted for the five Landsat scenes. Table 1 presents the areal extents of flathead lake in various categories of chlorophyll concentration. In general, 1980s show higher chlorophyll concentrations compared to the 1990s.:

Chlorophyll concentration mg/l	**July 16, 1984 %**	**July 27, 1988 %**	**July 20, 1991 %**	**July 1, 1996 %**	**August 3, 1999 %**
0 – 1	0.00	0.15	10.17	0.00	33.25
1 – 2	2.82	4.86	89.83	7.74	66.75
2 – 3	35.62	69.73	0.00	88.84	0.0
4 – 4.4	61.55	25.25	0.05	3.41	0.0

Table 1 – Percent of surface area in chlorophyll concentration classes as estimated from the five Landsat scenes.

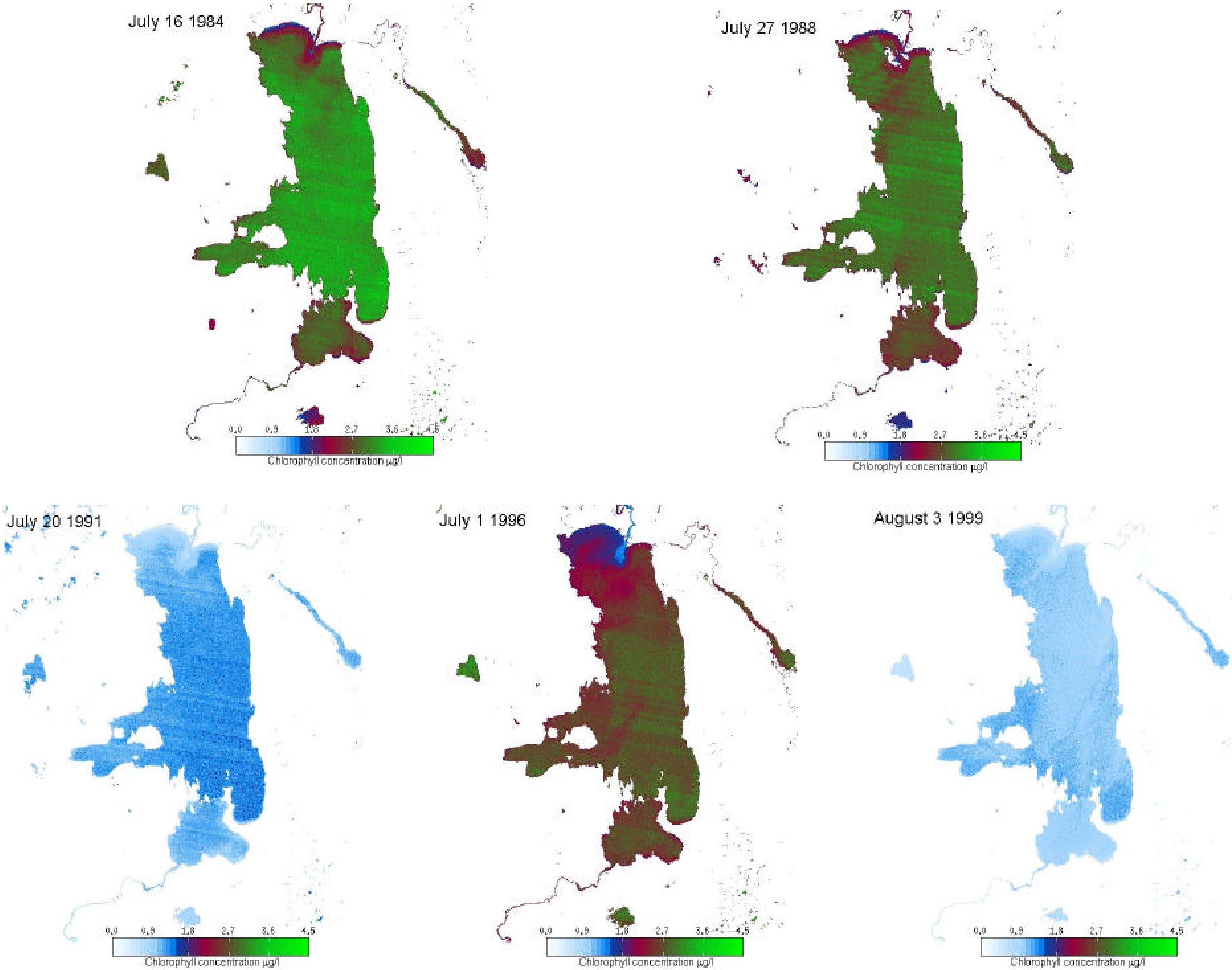

Figure 1 – Maps of chlorophyll concentration in mg/l estimated from the atmospherically corrected Landsat TM and ETM+ data using the model presented in equation 1.

Both Figure 1 and Table 1 show that the chlorophyll concentration was predicted to be the highest in 1984, followed by 1988 and 1996. In the years 1991 and 1999 the lake's chlorophyll concentration was estimated to be the lowest.

We explain this lower prediction of chlorophyll concentration as a result of higher streamflow and lower lake temperature in the years 1991 and 1999. In Table 2 we report the monthly streamflow in cubic feet/second recorded for the Flathead River near Columbia Falls for the different years of our analysis. In the month of July streamflow was the lowest in 1988 and in 1984, which show the highest predicted chlorophyll concentrations. Years 1991 and 1999, which have the lowest predicted chlorophyll concentrations, have the highest streamflows in the months of satellite data acquisition.

month	**1984**	**1988**	**1991**	**1996**	**1999**
1	1101	398	995	1456	710
2	853	395	1161	2017	602
3	820	546	1018	1574	1101
4	2848	3537	4147	5155	3340
5	5966	7430	12530	8932	7799
6	9004	5924	12720	14410	11360
7	3439	1739	6697	5470	5855
8	1440	858	2156	2124	2531
9	1142	662	1049	1306	1148
10	947	1175	727	1474	1435
11	877	1269	712	1103	3435
12	588	836	615	697	1419
total	29025	24769	44527	45718	40735

Table 2 – Monthly streamflow of the Flathead River near Columbia Falls in cubic feet/second.

In Figure 2 we show the temperature map of the lake surface for 1984 and 1991 as estimated from the thermal bands from the Landsat TM scenes. The temperature in 1991 was considerably lower than in 1984, and it can be expected that lower temperatures affect the magnitude of the algal blooms.

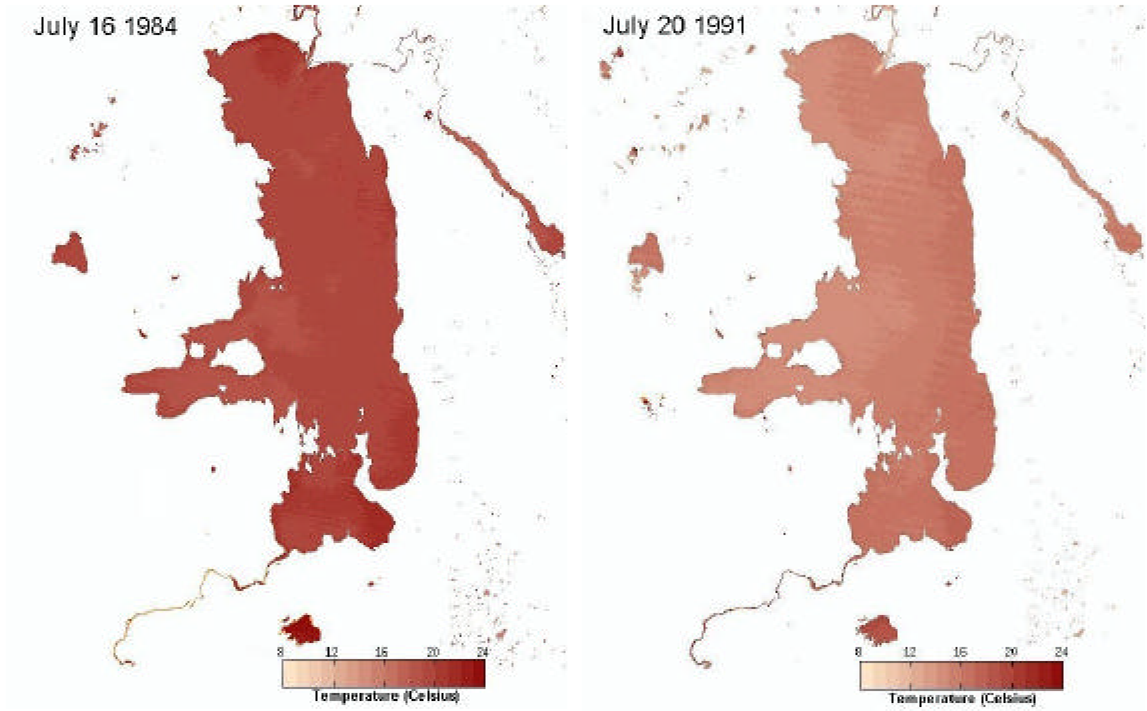

Figure 2 - Temperature map of the lake surface for 1984 and 1991 as estimated from the thermal bands of the Landsat TM scenes.

A more accurate estimation of the distribution of the chlorophyll concentration in the Flathead Lake could be obtained if geo-referenced ground measurements of the parameter (chlorophyll) are available. We suggest that water sampling should be performed at 5-6 locations around the lake. These measurements would allow a better calibration of the model presented in equation 1.

Conclusions

Landsat TM and ETM+ data have been used in a number of studies to estimate quality of inland waters. The advantages of this type of data are:

- suitable spatial resolution
- suitable spectral range of data acquisition
- long data record (1982 to present)
- affordable cost

The analysis of Landsat satellite data to map chlorophyll concentration in inland waters may provide a useful tool for gaining periodical information on the spatial distribution of algae.

Nevertheless, we suggest that ground measurements be available to improve the accuracy of the estimation of the chlorophyll distribution.

References

Brivio P.A., C. Giardino and E. Zilioli (2001) – Determination of chlorophyll concentration changes in Lake Garda using an image-based radiative transfer code for Landsat TM images. International Journal of remote sensing 22:2: 487-502.